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Development and Validation of a Shear Punch Test Fixture

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Contract Document Number: FR-SHEAR120331
PWGSC Contract Number: W7707-125448/001/HAL
Contract Project Manager: K.J. KarisAllen, 902-477-4062
Contract Scientific Authority: Dr. Allison Nolting, Project Authority, 902-427-3035

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Defence R&D Canada – Atlantic

Contract Report
DRDC Atlantic CR 2012-070
August 2013

Canada

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Defence R&D Canada – Atlantic

Contract Report
DRDC Atlantic CR 2012-070
August 2013

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Abstract

An experimental shear punch assembly has been designed and fabricated for the evaluation of mechanical strength properties of metallic materials. The shear punch tester uses very small, thin specimens to evaluate shear behaviour of materials, the results of which can be correlated to tensile behaviour of the material. The apparatus provides a means of evaluating the mechanical properties of metal matrix composites (MMC) manufactured by friction stir processing (FSP) that are being developed as part of a Technology Investment Fund (TIF) project, as the volume of materials produced are too small for conventional tensile test methods. The shear punch apparatus has a similar basic design to those described in the literature; however a close-coupled compression force transducer and the direct measurement of specimen displacement response during the test procedure have been incorporated. This provides a direct measurement of both force and specimen displacement which improves the accuracy of the measured material response. This report also details the validation of the apparatus using 3xxx series aluminium specimens. The results indicate that for a given punch diameter and specimen thickness combination, the calculated effective yield stress, ultimate stress and strain are generally reproducible.

Résumé

Un appareil expérimental d’essai de cisaillement et de perforation a été mis au point et fabriqué dans le but d’évaluer les propriétés de matériaux métalliques sur le plan de la résistance mécanique. Celui-ci ne nécessite que de très petits échantillons pour établir le comportement de matériaux soumis à un essai de cisaillement, dont les résultats peuvent être corrélés à la résistance à la traction des matériaux. L’appareil permet d’évaluer les propriétés mécaniques de composites à matrice métallique qui sont fabriqués par friction-malaxage dans le cadre d’un projet du Fonds d’investissement technologique, mais les quantités produites sont très petites pour se prêter à des essais de traction classiques. Sa conception fondamentale est similaire à celle d’autres appareils décrits dans des ouvrages pertinents, mais elle comprend un transducteur de force de compression à couplage direct et implique la mesure directe du mouvement des échantillons pendant les essais. L’appareil permet donc de mesurer directement le mouvement de la force et des échantillons, ce qui procure des mesures plus exactes de la réaction des matériaux éprouvés. Le présent rapport traite en détail de la validation de l’appareil au moyen d’échantillons d’aluminium de la série 3xxx. Les résultats de cette dernière montrent qu’en conjuguant un diamètre de perforation donné à une épaisseur d’échantillon particulière, il est généralement possible de reproduire la limite réelle d’élasticité, la contrainte de rupture et la déformation calculées.

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Executive summary

Development and Validation of a Shear Punch Test Fixture

K.J. KarisAllen; DRDC Atlantic CR 2012-070; Defence R&D Canada – Atlantic; August 2013.

Introduction: Through a Technology Investment Fund (TIF) project, DRDC Atlantic is leading a team of government departments and academics to develop a friction stir processing (FSP) based procedure to create metal matrix composite (MMC) surface layers on aluminum substrates. The FSP-MMC layer is intended to improve the ballistic resistance of the material or component that it is created on. The overarching goal of the TIF is to apply the FSP-MMCs to specific areas of structures or vehicle components that would benefit from improved ballistic performance. Applying the ballistic protection only to the areas where it was needed would allow for a unique combination of structural and ballistic performance and improve the survivability of Canadian Armed Forces assets.

The thinness of the surface layer created by this technique makes it difficult to evaluate the mechanical properties of the MMCs with conventional tensile tests. To address this issue, DRDC has, through a contract with FACTS Engineering, developed a shear punch tester to measure the shear properties of thin, small specimens. Results published in the open literature indicate that the tensile properties can be inferred from the shear punch properties. The goal of developing the shear punch tester was to provide DRDC with a means to evaluate the effect of FSP processing parameters on the mechanical properties of the MMCs and accurately determine which processes produce the best MMC layers.

Results: While the basic design of the apparatus is similar to those described in the open literature, a close-coupled compression force transducer and direct measurement of specimen displacement response during the test procedure make this a unique design. The results of validation experiments conducted with the apparatus indicate that with the exception of the 3 mm punch diameter and 0.28 mm specimen thickness combination, in general, for a given punch diameter and specimen thickness combination, the calculated effective yield stress, ultimate stress and strain are reproducible.

Significance: The shear punch tester allows DRDC Atlantic to evaluate the mechanical performance of materials that are too small to provide conventional tensile test specimens. In the context of the FSP-MMC TIF project, it provides a means to evaluate the effect of FSP parameters on the mechanical properties of the MMCs, which can be used to help optimize the ballistic performance of the MMC layer. If the overall TIF project is successful, it could provide the Canadian Armed Forces with the ability to locally enhance ballistic resistance on specific areas of complex vehicle or structural components, resulting in an improved combination of structural and ballistic performance for structures and vehicle components.

In addition to FSP MMCs, it is envisioned that the apparatus can be used to directly evaluate the mechanical properties of metallurgical zones within welds and through-thickness variation within thick metallic plates. This could help to optimize welding procedures for decreased distortion and residual stresses, which could in turn decrease operating costs of platforms through decreased fuel

costs (due to improved fairness of the hull) and decreased hull maintenance costs (due to improved fatigue performance).

Future Plans: The shear punch tester will be used to evaluate the effect of FSP processing parameters on the mechanical properties of the MMCs created for the TIF project. The most optimal processing parameters will be identified and used to create ballistic test specimens. Testing of these specimens will provide a measure of how the FSP-MMC layer affects ballistic performance, and will determine whether or not this technology is likely to provide strategic advantage to the Canadian Armed Forces.

Sommaire

Development and Validation of a Shear Punch Test Fixture

K.J. KarisAllen; DRDC Atlantic CR 2012-070; R & D pour la défense Canada – Atlantique; août 2013.

Introduction : Dans le cadre d'un projet du Fonds d'investissement technologique (FIT), RDDC Atlantique dirige une équipe dont les membres proviennent de ministères gouvernementaux et du milieu universitaire et sont chargés d'élaborer une procédure de friction-malaxage (FM) conçue pour produire des couches de composites à matrice métallique (CMM) à la surface de substrats d'aluminium. Les couches de CMM visent à améliorer la résistance balistique du matériau ou du composant qu'elles recouvrent. Le projet du FIT a pour principal objet d'appliquer les CMM produits par FM à des parties données de composants de structures ou de véhicules, afin d'améliorer le rendement balistique. La protection balistique des parties qui l'exigent a pour avantage unique d'améliorer du même coup le rendement structural et balistique, ainsi que la surviabilité du matériel des Forces armees canadiennes.

La minceur des couches superficielles de CMM produits par FM fait en sorte qu'il est difficile d'évaluer les propriétés mécaniques des CMM au moyen d'essais de traction classiques. Pour résoudre ce problème, RDDC a mis au point un appareil d'essai de cisaillement et de perforation, dans le cadre d'un contrat avec FACTS Engineering, afin de pouvoir mesurer les propriétés d'échantillons minces et petits soumis à un cisaillement. Des résultats publiés dans des ouvrages non classifiés montrent que les propriétés de traction peuvent être induites des propriétés de cisaillement et de perforation. En concevant l'appareil susmentionné, RDDC visait à trouver un moyen d'évaluer l'effet des paramètres de FM sur les propriétés mécaniques des CMM, de même qu'à déterminer exactement quels procédés permettent de produire les meilleurs couches de CMM.

Résultats : Bien que la conception fondamentale de l'appareil soit similaire à celle d'autres dispositifs décrits dans des ouvrages non classifiés, elle demeure unique en ce sens qu'elle comprend un transducteur de force de compression à couplage direct et implique la mesure directe du mouvement des échantillons pendant les essais. Les résultats des expériences de validation réalisées avec l'appareil montrent qu'en conjuguant un diamètre de perforation donné à une épaisseur d'échantillon particulière, il est généralement possible de reproduire la limite réelle d'élasticité, la contrainte de rupture et la déformation calculées, sauf dans le cas d'un diamètre de perforation de 3 mm combinée à une épaisseur de 0,28 mm.

Portée : Grâce à son appareil d'essai de perforation et de cisaillement, RDDC Atlantique peut évaluer le rendement mécanique de matériaux trop petits pour se prêter au prélèvement d'échantillons d'essais de traction classiques. Dans le contexte du projet du FIT visant la production de CMM par FM, cet appareil permet d'évaluer l'effet des paramètres de FM sur les propriétés mécaniques des CMM, afin de faciliter la maximisation du rendement balistique des couches de CMM. Si le but global du projet est atteint, les Forces canadiennes pourraient améliorer la résistance balistique de parties données de composants complexes de structures ou de véhicules, afin d'en accroître le rendement structural et balistique global.

L’appareil pourrait aussi se prêter à l’évaluation directe des propriétés mécaniques de zones métallurgiques précises dans des soudures, ainsi que de la variation en fonction de l’épaisseur des propriétés d’épaisses plaques métalliques. Une telle application pourrait faciliter l’optimisation des procédures de soudage, afin de réduire la déformation des matériaux et les contraintes résiduelles et, du même coup, de réduire les coûts d’exploitation des plateformes grâce à une diminution des coûts de carburant (uniformité accrue des caisses) et d’entretien des caisses (résistance accrue à la fatigue).

Recherches futures : L’appareil d’essai de perforation et de cisaillement servira à évaluer l’effet des paramètres de FM sur les propriétés mécaniques des CMM produits dans le cadre du projet du FIT. Les paramètres de FM optimaux seront identifiés, afin de produire des échantillons d’essai balistique. La mise à l’essai de ces échantillons servira à déterminer comment les couches de CMM produits par FM influent sur le rendement balistique et si le traitement par FM pourrait constituer un avantage stratégique pour les Forces canadiennes.

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1 INTRODUCTION

DRDC Atlantic has initiated a research project for the development of a friction stir process to fabricate surface metal matrix composites in aluminum alloys for potential application in light armoured vehicles. The relatively thin layer created by the friction stir process, together with the small size of the coupons available to date, are not conducive to evaluation using conventional standardized procedures [1].

Published studies indicate that a correlation exists between tension and shear properties of metallic materials [2,3]. The experimental procedure employed for the measurement of the shear properties involves the generation of a small circular disc from the candidate material using a matched punch/die assembly. The force and displacement sustained by the disc during the process are recorded and subsequently post processed to provide the points of correlation.

The primary objectives of the current contracted work are twofold. The first objective entails the design and fabrication of an experimental shear punch assembly for the evaluation of the mechanical properties of metallic materials. The second objective is the experimental evaluation of the assembly using a standardized metallic alloy chemistry with predictable tension properties. The following sections describe the assembly designed and fabricated, together with a series of experimental test results used to characterize the accuracy and reproducibility of the apparatus.

2 DESIGN OF THE SHEAR PUNCH TEST FIXTURE ASSEMBLY

2.1 General Requirements

The primary objective of the current work is the design, fabrication, and integration of a shear punch test fixture (SPTF) for utilization with a MTS Model 370 series servo-hydraulic materials test system. The basic components of the fixture consist of a precision machined punch and die set which applies a compressive force to a thin sheet of metallic material. In order to fully evaluate the mechanical properties of the material subsequent to the test protocol, a means of measuring the applied shear force and specimen deflection must be integrated into the fixture design. Figure 1 shows a schematic representation of the general design of the shear punch test fixture fabricated to meet the requirements.

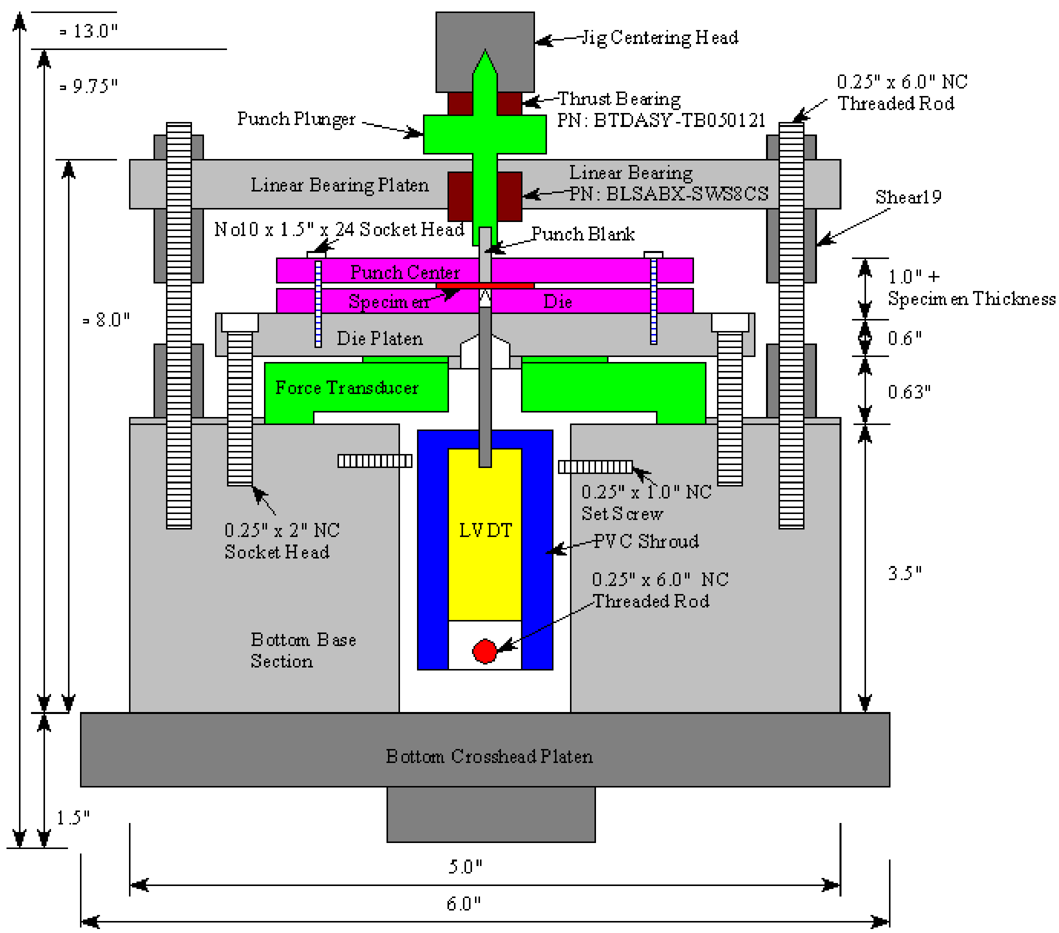

Figure 1: Schematic showing the general design of the shear punch test fixture fabricated to meet the requirements.

The design includes a self-centering specimen holder for maintaining the requisite alignment/tolerances between the punch and the die during the test procedure. An additional jig centering head was incorporated into the design of the fixture to ensure that the entire fixture was centered with respect to the longitudinal centroid of the MTS 370 actuator, as well as provide lateral support to the top section of the punch. The inclusion of the jig centering head minimized the possibility of introducing asymmetric loading between the actuator and the punch during the test procedure. In addition, the magnitude of the gap between the bottom surface of the centering head and the top surface of the housing shroud was designed to be adjustable in order to shunt the actuator load subsequent to a predefined magnitude of head (punch) deflection by the actuator. Thus, an initial head/shroud gap can be defined which facilitates the requisite applied deflection of the punch on the specimen during testing and subsequently shunts load to the shroud prior to contact between the bottom surface of the punch collar and the specimen holder. Shunting load subsequent to a predefined deflection minimized the possibility of inadvertently overloading the relatively low range force transducers required by the project.

2.2 Design of the Fixture Components and Assembly Instructions

The bottom base section of the test fixture proposed in Figure 2 has been designed to remain unattached to the servo-hydraulic load frame and sits on the bottom crosshead platen (Figure 3). The bottom crosshead platen is attached to the MTS 370 force transducer via an M12 x 1.25 threaded male coupling. The upper jig self-centering head (Figure 4) is also attached to the upper load frame actuator via an M12 x 1.25 threaded male coupling. In this fashion the attachment design does not permanently alter the basic configuration of the MTS load frame. It also facilitates a relatively simple initial setup procedure, as well as test-to-test positioning replication owing to the inclusion of the upper self-centering head included in the design.

Two (2) interchangeable LVDT transducers (Omega model LD500) with respective ranges of ±1mm, and ±2.5 mm have been supplied with the fixture (Figure 5). The Model LD500 has a specified linearity and repeatability of ±0.25% and ±0.15 µm, respectively. The outer coil shroud for the model is approximately 0.74 inches which makes it compatible with a coaxial configuration with the force transducer. The actuator of the LVDT is also spring loaded which ensures that contact between the transducer tip and the bottom surface of the specimen is maintained throughout the test procedure (direct measurement). The model LD500 generates a DC output signal which facilitates integration into the MTS system acquisition and control hardware.

The first step in the assembly of the fixture is the insertion of the LVDT into the fabricated acetal polymer shroud (Figure 6). During this procedure the LVDT signal wire should be positioned perpendicular to the axis of the 0.25 inch threaded holes located at the bottom of the shroud. LVDT insertion is conducted by applying a gentle force on the bottom surface of the LVDT while ensuring that the upper LVDT extension is coaxial with the upper clearance hole in the shroud. Once the LVDT is fully inserted, the position is fixed using the nylon set screws located on the cylinder face of the shroud. Figure 7 shows a photograph of a LVDT properly inserted into one of the shrouds provided.

The second step in the assembly of the fixture is the insertion of the LVDT (with shroud) into the bottom base section (Figure 2). Prior to inserting the LVDT, ensure that the set screws located on the upper section of the base are adjusted to facilitate the clearance of the shroud. The procedure consists of inserting the shroud into the bottom of the base. Once inserted, thread the 0.25 inch threaded rod provided from the outer surface of the base clearance holes through the female threads located at the bottom of shroud. Continue to thread the rod through the shroud until equal sections of threaded rod ends are available on diametrically opposed sides of the base section. Using the wing nuts provided, secure the initial vertical position of the LVDT by threading them onto the exposed ends of the 0.25 inch threaded rod. At this stage, the four (4) threaded rods used to adjust the upper linear bearing platen position (with two (2) threaded collars each) may be threaded into the mating threaded holes (outer circumference holes) located on the upper surface of the base section. Once inserted, the bottom collar on each rod may be adjusted downward until the bottom surface of the collar is in firm contact with the upper surface of the base. Fix the position of the bottom collar using the set screws provided. Install and secure the bottom crosshead platen (Figure 3) and upper jig self-centering head (Figure 4). Set the assembled base section on the bottom crosshead platen (Figure 8).

Three (3) interchangeable compression force transducers (Omega model LC8200 series) with respective capacities of 250 lbsf, 1000 lbsf, and 3000 lbsf have been supplied with the fixture (Figure 9). The transducers have a nominal outer diameter of approximately 2.0 inches. To facilitate the insertion of a coaxial LVDT transducer in the fixture design, a force transducer design with an approximately 0.875 inch through hole was utilized. The Model LC8200 has a specified linearity and repeatability of ±0.5% and ±0.1%, respectively. Each force transducer was supplied with a 5 point NIST traceable calibration document.

The third step in the assembly of the fixture is the insertion of the force transducer and the coupling of the die platen to the fixture (Figure 10). The force transducer is integrated into the fixture by inserting it into the circular recess provided in the upper surface of the base section. During the insertion process, ensure that the transducer is orientated correctly (see Figure 9 indicating transducer upper surface). Insert collar of the die platen into the force transducer clearance hole. Prior to securing the die platen to the base section, connect the LVDT and the force transducers to the MTS signal acquisition hardware using the cables provided and activate the software utilized for monitoring the signals. Using the four (4) threaded socket-head fasteners provided, connect the die platen to the base section. Sequentially adjust diametrically opposed fasteners (uniform force applied by each fastener) until a compression force of approximately 10 lbsf is detected by the MTS software. Attach one of the bottom dies to the die platen using the four (4) socket-head fasteners provided. Adjust the vertical position of the LVDT (by loosening the wing nuts) until the plane representing the upper surface of the attached bottom die is within the calibrated range of the depressed contact tip of the LVDT as indicated by the MTS software. Adjust the lateral position of the LVDT tip using the four (4) set screws provided on the upper portion of the base section until the tip is concentric with the die clearance hole. Once completed, remove the bottom die from the die platen.

In order to ensure the accuracy and repeatability of the shear punch tests conducted, the design of the specimen holder must guarantee that the axial alignment of the punch and die components is maintained and that the load bearing surfaces of the punch, die, and specimen are initially parallel with respect to each other and orthogonal to the direction of the applied deflection generated by the actuator. Four (4) matched punch and die sets with nominal punch disc diameters of 3 mm, 4 mm, 5 mm, and 6 mm have been provided with the assembly. Each set consists of hardened die (Figure 11) and punch blanks (approximately 1 inch long) together with a matched punch centering disc (Figure 12) and a punch plunger (Figure 13). The hardness of the dies and punch blanks provided was approximately Rockwell "C" 62.

The fourth step in the assembly of the fixture is mounting the specimen between the die and the punch centering disc. The procedure may be conducted on a surface away from the partially assembled fixture for increased access to the components if desired. Set the die (heat tinted component) on a flat surface with the "X" mark on the die cylinder positioned up. Insert the four (4) locating posts provided into the appropriate die clearance holes. Position the specimen over the die punch hole. With the "X" mark on the punch centering disc positioned down, circumferentially align the centering disc "X" mark with the corresponding mark on the die. Slide the punch centering disc clearance holes onto the protruding ends of the die locating posts (this step may require a sequence of gentle taps on the upper surface of the punch centering disc). Transfer the assembled specimen holder to the upper surface of the die platen (partially assembled test fixture) and secure to the platen using the four (4) socket-head fasteners provided. Insert the appropriate punch blank into the upper surface of the clearance hole provided in the punch centering disc. Install the upper linear bearing platen (Figure 14) onto the four (4) threaded rod ends previously installed in step 1. Insert the punch plunger into the linear bearing and adjust the four (4) threaded rod upper collars until the clearance hole in the end of the plunger slides freely over the end of the punch blank. The vertical space between the bottom surface of the plunger collar and the upper surface of the linear bearing platen may be adjusted by the collars for the protection of the LVDT and force transducer if desired (provides a load shunt after a predetermined applied plunger deflection). Insert the thrust bearing provided over the upper end of the punch plunger (post contact bearing diameter positioned down).

The fifth and final step in the procedure is centering the assembled fixture with respect to the MTS load frame actuator axis. Centering may be conducted by iteratively lowering the vertical height of the actuator and manually adjusting the position of the assembled fixture until the clearance hole in the bottom surface of the upper jig self-centering head (installed in step 1) slides freely over the upper tapered end of the punch plunger (installed in step 4). Figure 15 shows a photograph of the completely assembled shear punch test fixture during one of the system verification tests conducted. It should be noted that once the fixture has been successfully assembled, only the fourth and fifth steps require operator attention between successive tests conducted.

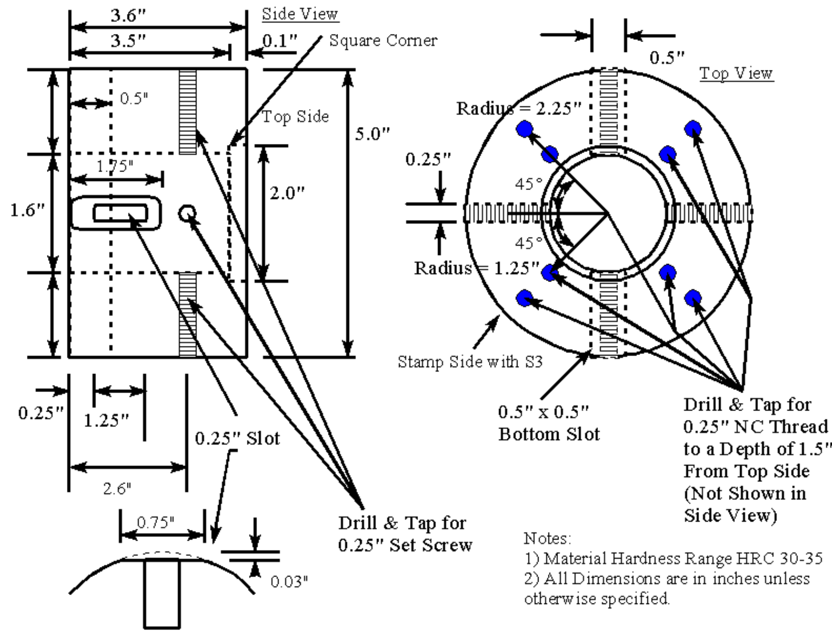

Figure 2: Schematic showing the general dimensional design requirements of the bottom base section of the shear punch test fixture.

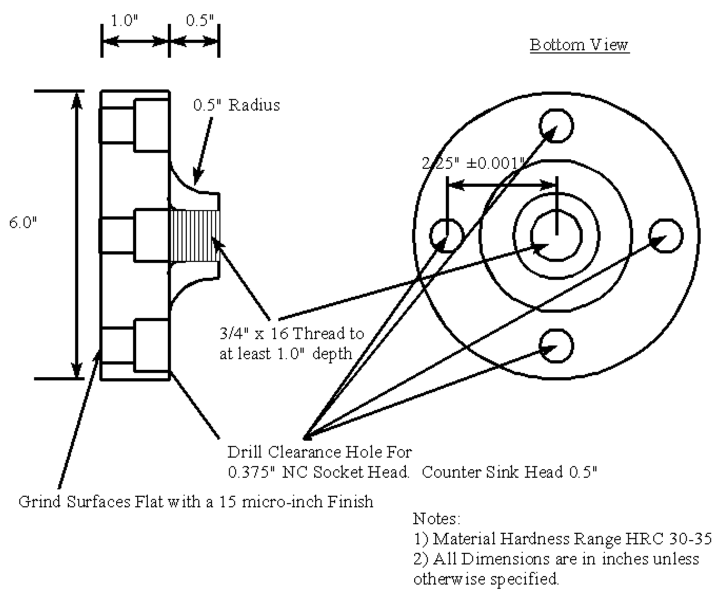

Figure 3: Schematic showing the general dimensional design requirements of the bottom platen of the shear punch test fixture.

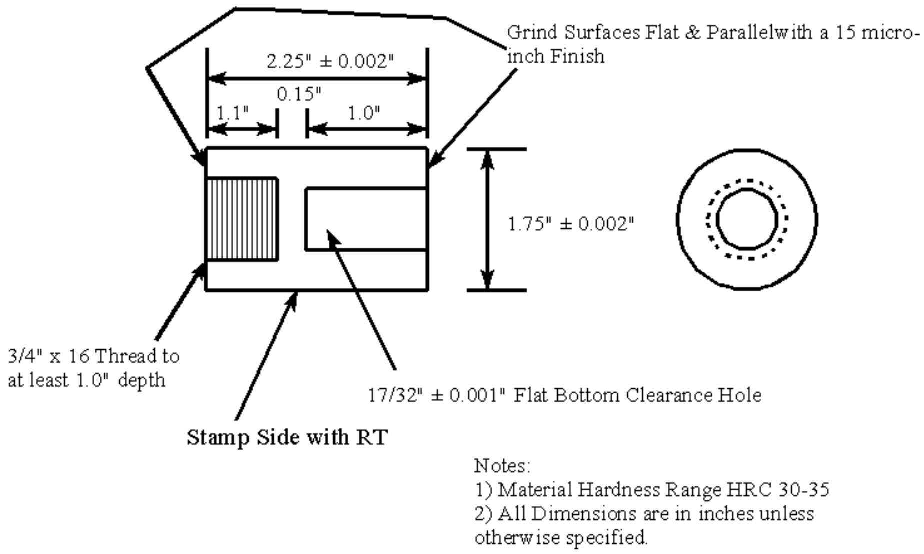

Figure 4: Schematic showing the general dimensional design requirements of the upper self centering head fabricated for the shear punch test fixture.

Figure 5: Photograph showing one of the LVDT transducers provided with the shear punch test fixture.

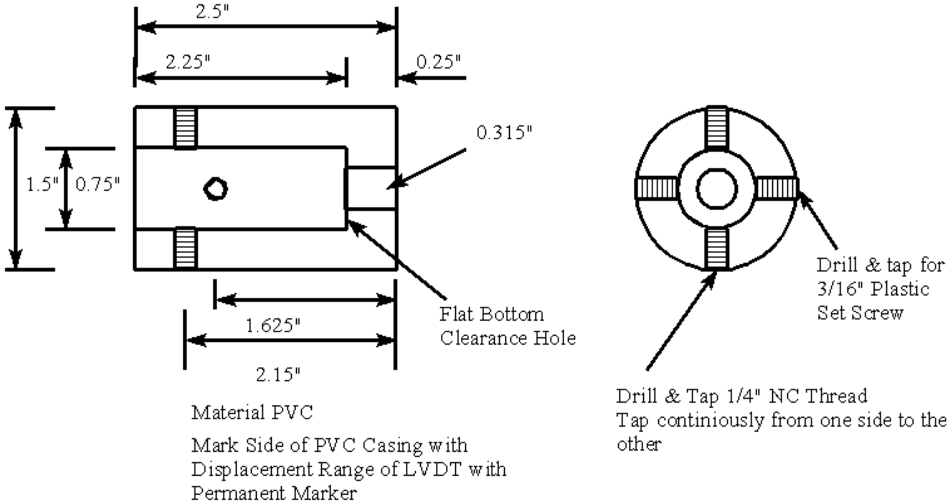

Figure 6: Schematic showing the general dimensional design requirements of the acetal polymer LVDT shroud fabricated for the shear punch test fixture.

Figure 7: Photograph showing a LVDT transducer installed in a polymer shroud.

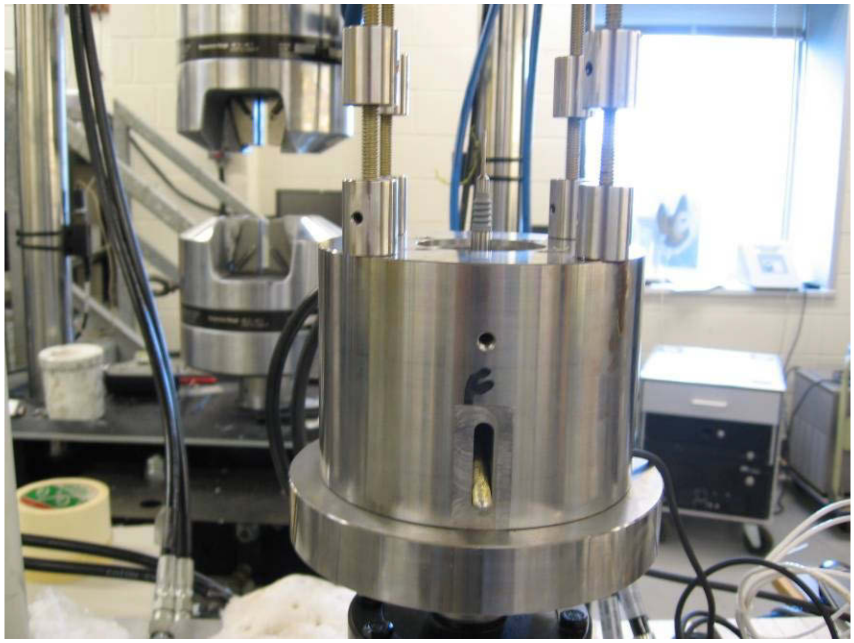

Figure 8: Photograph showing the partially assembled fixture sitting on the bottom platen.

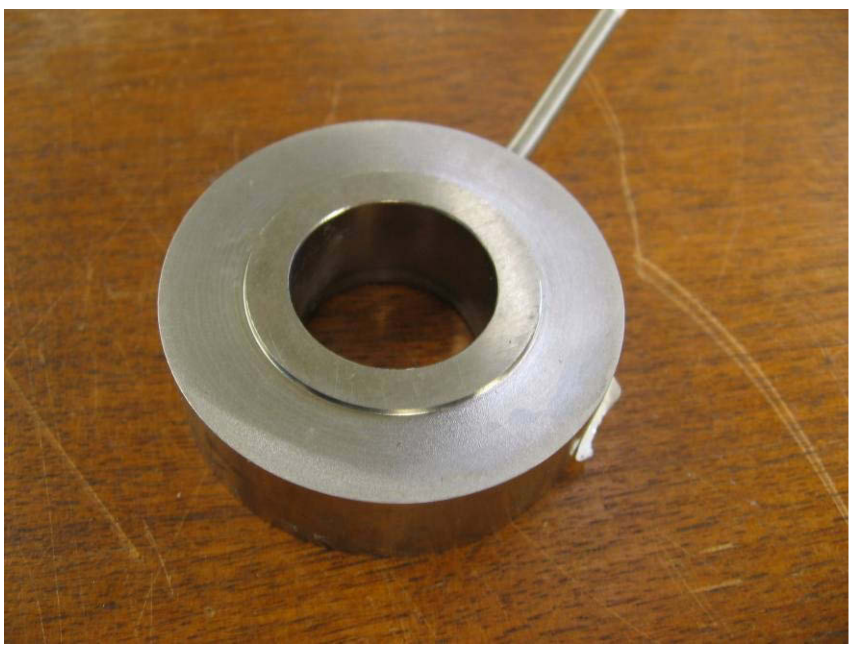

Figure 9: Photograph showing the upper surface of one of the compression force transducers provided with the fixture.

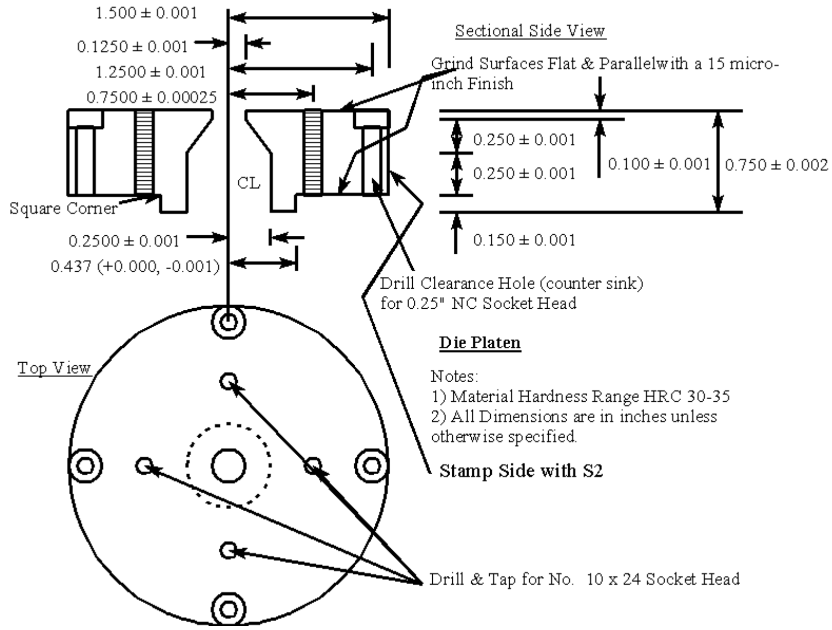

Figure 10: Schematic showing the general dimensional design requirements of the die platen fabricated for the shear punch test fixture.

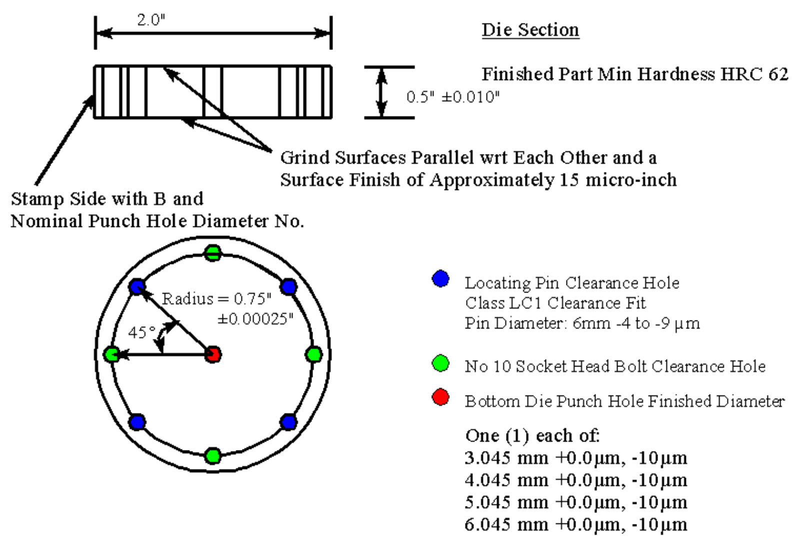

Figure 11: Schematic showing the general dimensional design requirements of the dies fabricated for the shear punch test fixture.

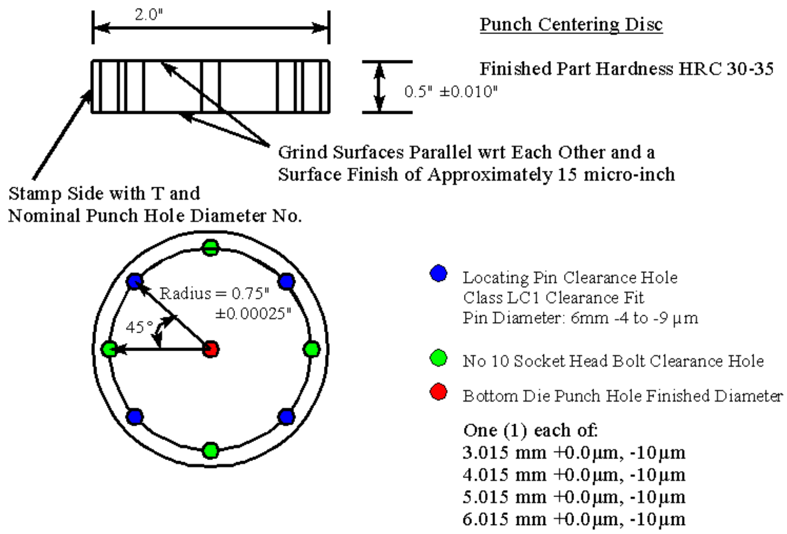

Figure 12: Schematic showing the general dimensional design requirements of the punch centering discs fabricated for the shear punch test fixture.

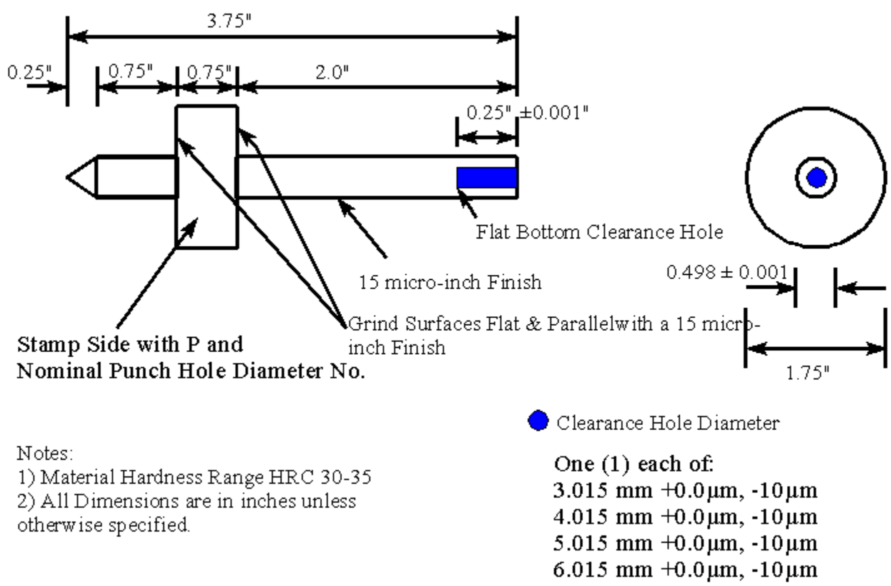

Figure 13: Schematic showing the general dimensional design requirements of the punch plungers fabricated for the shear punch test fixture.

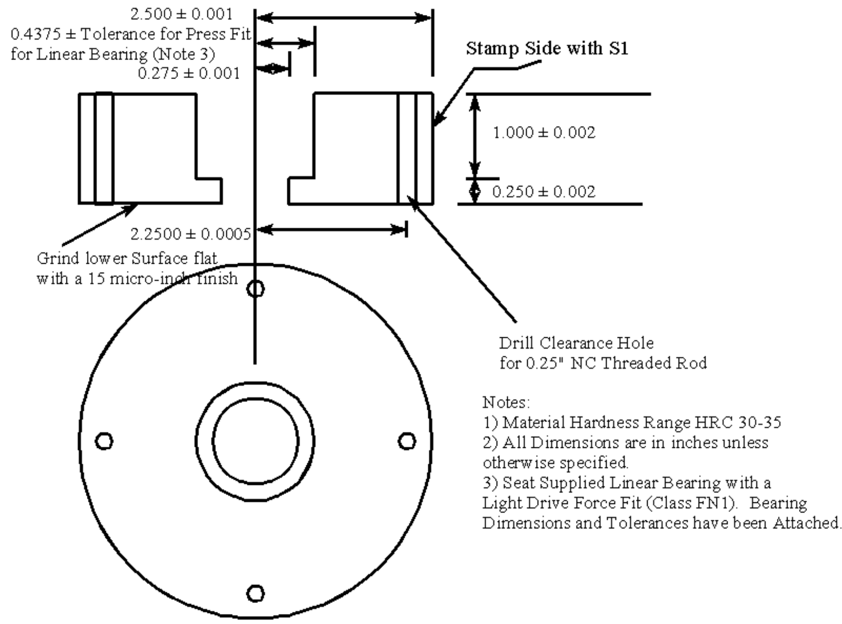

Figure 14: Schematic showing the general dimensional design requirements of the upper linear bearing platen fabricated for the shear punch test fixture.

Figure 15: Photograph of the assembled shear punch test fixture during one of the system verification tests conducted.

3 EXPERIMENTAL VERIFICATION OF THE SHEAR PUNCH TEST FIXTURE

3.1 Experimental Procedure

Table 1 summarizes the test matrix used to evaluate the accuracy and reproducibility of the shear punch assembly. The material utilized for the tests was an aluminum 3003 alloy chemistry with an annealed temper. Triplicate tests were conducted with two (2) of the four (4) matched punch and die sets fabricated (3 mm and 6 mm) for specimen thicknesses of 0.28 mm and 0.70 mm. For each matched punch and die set, the gap tolerance between the punch shank and die clearance hole was approximately 0.0225 mm.

The specimen force and LVDT transducer sensors utilized for the series of tests executed had full scale ranges of 4.448 kN and ±2.5 mm, respectively. The force and displacement signals generated by the transducers were routed into the MTS Model 370 hardware signal conditioners and acquired using FlexTest™ software algorithms. Prior to the initiation of the test sequence, the FlexTest™ software signal interlocks were activated to provide appropriate protection for the integral force and displacement transducers included in the fixture design. A monotonic compression displacement was applied to the specimen coupons under stroke control with actuator displacement rates of 0.001 mm/s and 0.0005 mm/s for the 0.70 mm and 0.28 mm thick specimens, respectively. The conditioned signals for each test were saved to a non-volatile medium for subsequent post processing. Specimen retrieval subsequent to testing was achieved by inserting the punch blank into the bottom of the die clearance hole and gently pushing the specimen slug out through the top orifice.

In addition to the shear punch test conducted, duplicate uniaxial tensile tests were conducted in accordance with ASTM E08 [1] for comparison purposes. The cross-sectional area of the specimens was approximately 16.0 mm^2. An extensometer with a gauge length of approximately 50 mm was utilized for the determination of specimen strain during the tests.

Table 1: Summary of the test matrix used to evaluate the accuracy and reproducibility of the shear punch assembly.

Specimen Thickness (mm)	Tests Conducted for Indicated Punch Shank Diameter	
	3 mm	6 mm
0.28	3	3
0.70	3	3

3.2 Verification Test Results

Table 2 summarizes the results for the uniaxial tensile tests conducted. The 0.2 % yield stress (σ_y), ultimate stress (σ_{UTS}), and the strain to failure (ε_f) were approximately 59.2 MPa, 110.9 MPa, and 26.3 percent, respectively. The results generated for the annealed aluminum 3003 material were consistent with published data for the alloy specification and temper [4].

Table 2: Summary of the results for the uniaxial tension tests conducted.

Specimen	Yield Stress (MPa)	Ultimate Stress (MPa)	Failure Strain (%)
Al1	58.0	108.8	25.3
Al2	60.4	112.9	27.3
Average	59.2	110.9	26.3

Figure 16 through Figure 19 show graphical representations of the force-displacement relationships generated for the shear punch tests conducted. Each figure contains the results for the triplicate tests performed for a given combination of punch diameter and specimen thickness. For the test matrix executed, the results indicate that the morphology of the force-displacement relationship is similar regardless of the diameter of the punch utilized and specimen thickness. Each trace is generally described by three distinct intervals of differing character (Figure 20). Upon the initial deflection of the specimen, the trace exhibits a linear relationship between the applied force and displacement with a positive slope (Stage I). Continued deflection of the specimen beyond the initial linear section results in a non-linear interval with the force increasing to a maximum followed by an observed reduction in force (Stage II). The non-linear portion of the relationship is subsequently followed by a second approximately linear interval with a negative slope (Stage III). Dependent on the punch diameter/ specimen thickness combination tested, an additional interval (Stage IV) was observed in the trace which again exhibits an approximately linear relationship between force and displacement with a significantly smaller negative slope as compared to that observed in the Stage III interval.

For each data record, three points were selected from the force-displacement relationship for correlation with the results generated by the uniaxial tensile tests. The points selected and the equations used in the current study to convert the force and displacement data into effective stress and strain parameters were consistent with those utilized by other researchers conducting similar experiments [2]. The first point corresponds to the maximum force (P_{Max}) generated during the loading procedure which, when normalized by the specimen area of shear (die circumference × specimen thickness), was correlated to the ultimate uniaxial tensile stress (σ_{UTS}). The second point selected is generated by conducting a least squares regression analysis using the Stage I data between $0.1P_{Max}$ and $0.4P_{Max}$. The force defined by the intersection of the 0.2 percent (of specimen thickness) offset to the slope generated by the regression analysis was correlated to the uniaxial yield stress (σ_y). The 0.2 percent offset was arbitrarily chosen to be consistent with that utilized with the analysis of the uniaxial tension data [1]. Similar to the ultimate stress calculation, the load selected was normalized by the shear area (die circumference × specimen thickness). The final point selected is generated by conducting a least squares regression analysis using the Stage III data. The displacement defined by the intersection of the -0.2 percent (of specimen thickness) offset to the slope generated by the regression analysis was correlated to the uniaxial failure strain (ε_y) by subtracting the elastic specimen displacement (based on the -0.2 percent offset load and the Stage I regression slope previously described). Figure 20 shows a graphical representation of the displacement point (D_f) selected for the calculation of the strain parameter. The failure strain was normalized by the specimen thickness.

Figure 23 shows a scanning electron microscope image of the typical topographical features observed on the edge of the circular slug generated by the shear punch fixture. In general, the edge of the slug exhibited two distinct bands with differing surface characteristics. The first band extending from the bottom (die) surface to approximately 50 percent of the thickness revealed the presence of a relatively smooth, featureless surface. The morphology of this band of material is consistent with primary shear of the material owing to the punch displacing the material into the die. The second band extending from the top (punch) surface of the coupon to approximately 50 percent of the thickness exhibited an elongated texture in the direction of the punch displacement. Figure 24 shows the elongated void formation observed on the section of the slug edge adjacent to the top (punch) surface. The morphology of this band of material is consistent with Mode II tearing of the material. In addition to the Mode II tearing, dispersed areas secondary shear were observed within the band (Figure 25). Overall the general morphology of the slug edge is typical of a Type 4 appearance [6] which is consistent with the targeted punch to die clearance combined with the material thickness and mechanical properties.

Table 3 summarizes the effective stress and strain parameters generated from the shear punch test experiments conducted. With the exception of the 3 mm punch diameter and 0.28 mm specimen thickness combination, the results indicate that, in general, for a given punch diameter and specimen thickness combination, the calculated effective yield stress, ultimate stress and strain are reproducible. A comparison of the results generated by the differing punch diameter and specimen thicknesses combinations indicates a good agreement between the effective stress parameters calculated using the 6 mm punch diameter for the specimen thicknesses tested. Effective stress values from the 3 mm punch diameter tests were elevated as compared with the 6 mm diameter tests and tended to increase with decreasing specimen thickness. The effective strain parameter calculated exhibited reasonable agreement between 3 mm and 6 mm punch diameters for the 0.70 mm and 0.28 mm thick specimen experiments conducted.

One possible contribution to the punch diameter and specimen thickness variations observed is the metallurgical condition of the material evaluated. Previous studies conducted [2,5] have indicated a dependence of the effective stress and strain values generated by the shear punch procedure on material grain size. It has been recommended that a minimum of approximately 25 grains be sampled within the process zone for the assessment of the bulk mechanical properties of a material using the shear punch procedure [2,5]. Figure 26 shows an example of the typical micrograph observed for the 0.70 mm and 0.28 mm material utilized for the experiments. Analysis of the microstructures indicates a similar average grain size for both coupon thicknesses with an average diameter of approximately 45 µm. For the measured grain size, significantly greater than 25 grains are deformed within the annular process zone for both the 3 mm and 6 mm punch diameters. Thus, based on the literature [2,5], the grain size of the material tested does not account for the elevated effective stress values observed for the 3 mm punch diameter configuration as compared with the 6 mm diameter configuration.

A second possible explanation for the variations in effective stress observed for the 3 mm punch diameter configuration is the interaction of the relatively complex state of stress applied to the specimen coupon during the procedure. Identified sources to the stress state include compression, tension, bending, and shear [2]. Given that the requisite tests for evaluating contributions from these sources was outside the scope of the current study, it is recommended that the appropriate test matrix of material properties, coupon thicknesses, and fixture configurations be evaluated to assess the dependence of the effective stress on the respective parameters during various stages of the test procedure.

As indicated previously, the points selected and the equations used in the current study were consistent with those utilized by other researchers conducting similar experiments [2]. While the basic design of the apparatus fabricated for the current study is similar to those described in the literature, the close-coupled compression force transducer and the direct measurement of specimen displacement response included in the current design is atypical (both are measured by remote transducers in the designs described in the literature). Given the relatively complex stress state(s) applied to the specimen during the test, the current design may provide an ideal platform for experimentally isolating and characterizing the various contributions to specimen response throughout the test. Such characterization may provide differing points (and possibly additional insight) with respect to correlations with the bulk mechanical properties of the materials evaluated.

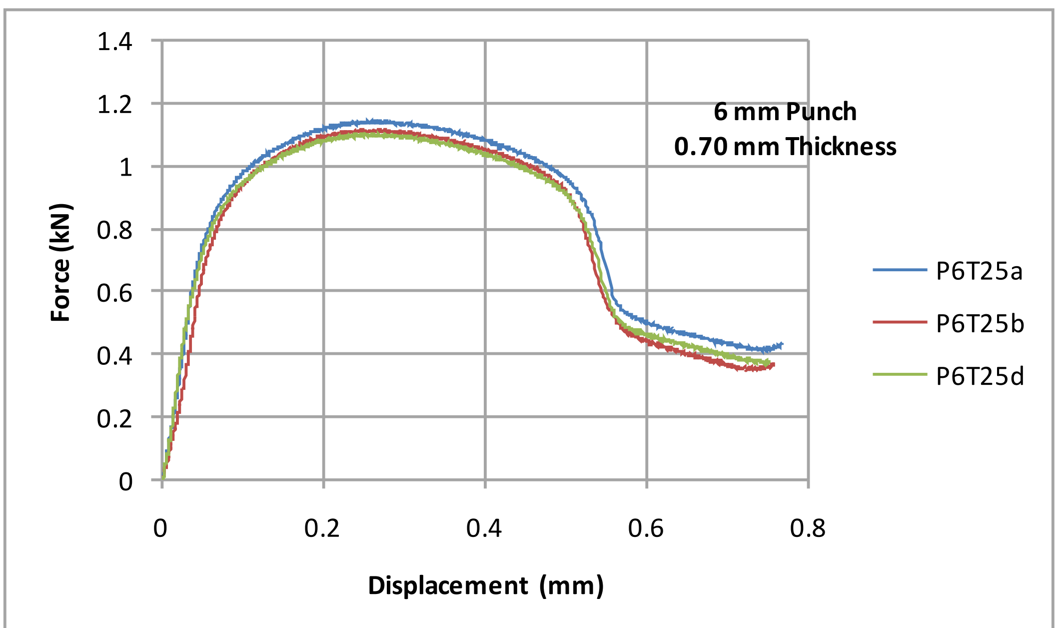

Figure 16: Graphical representation of the force-displacement relationships generated for the tests conducted with a punch diameter of 6 mm and a specimen thickness of 0.70 mm.

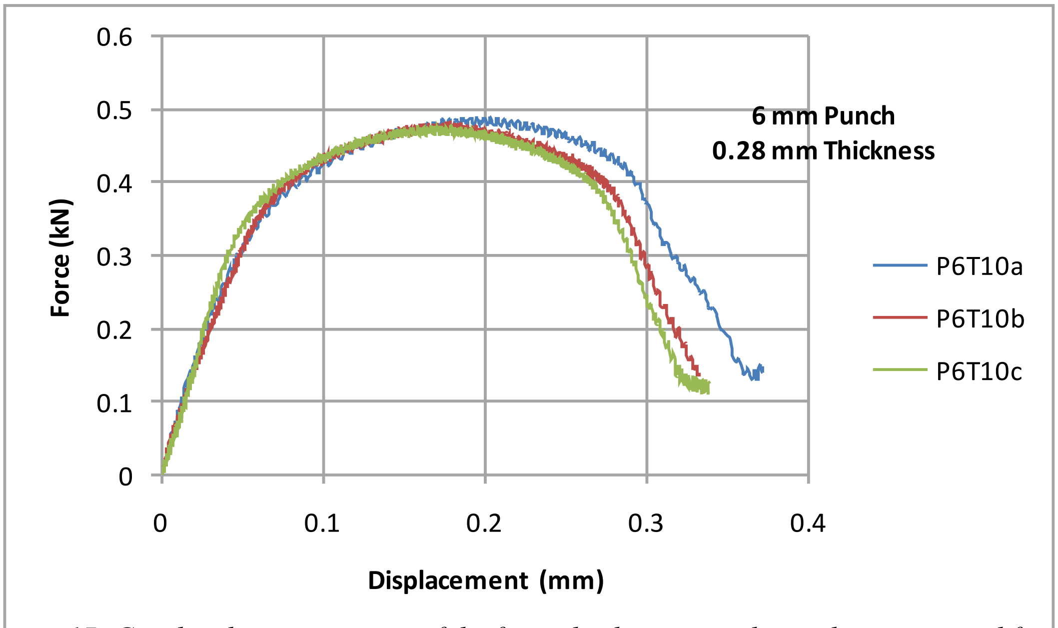

Figure 17: Graphical representation of the force-displacement relationships generated for the tests conducted with a punch diameter of 6 mm and a specimen thickness of 0.28 mm.

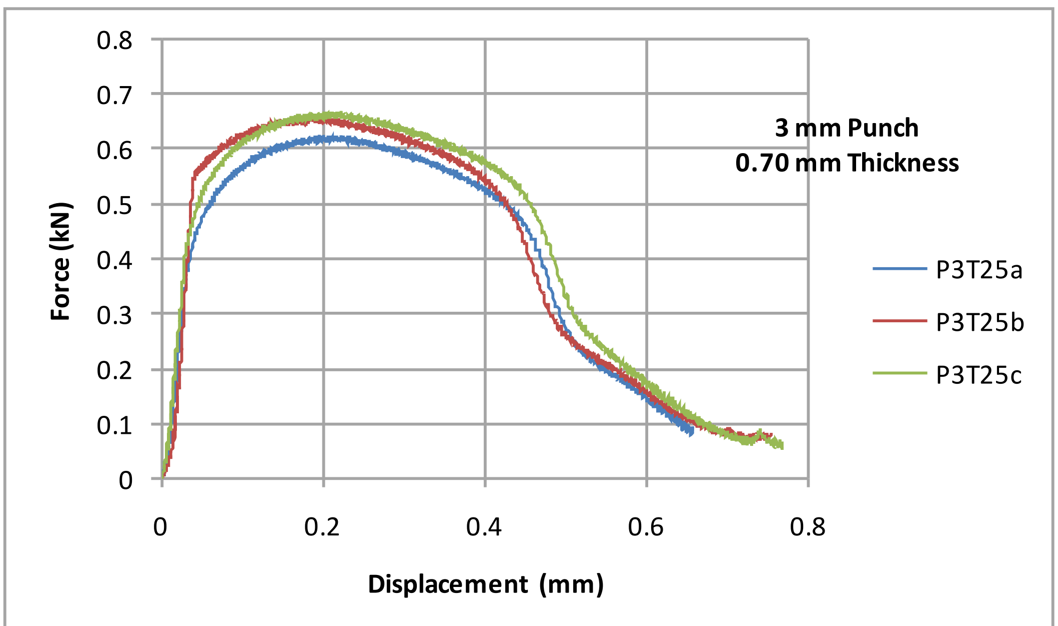

Figure 18: Graphical representation of the force-displacement relationships generated for the tests conducted with a punch diameter of 3 mm and a specimen thickness of 0.70 mm.

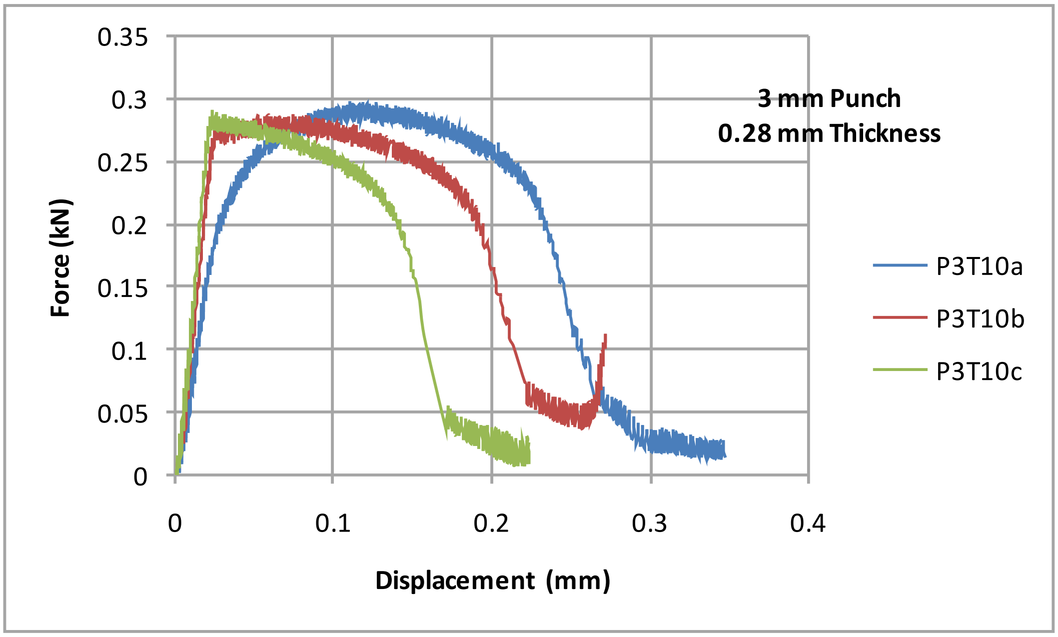

Figure 19: Graphical representation of the force-displacement relationships generated for the tests conducted with a punch diameter of 3 mm and a specimen thickness of 0.28 mm.

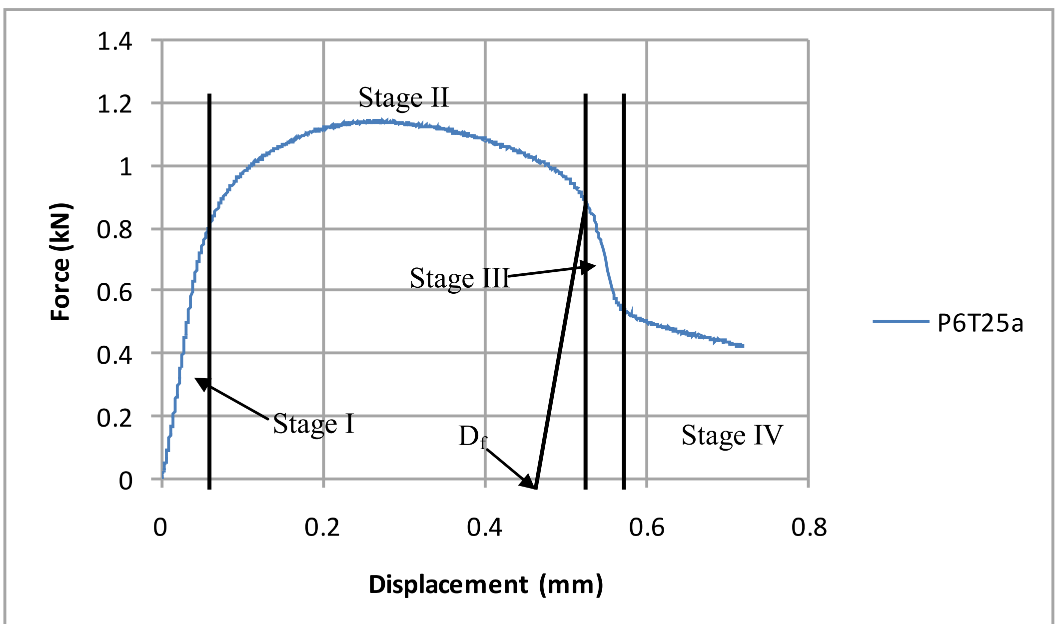

Figure 20: Force-displacement record showing the four intervals of differing morphology observed for the shear punch tests conducted.

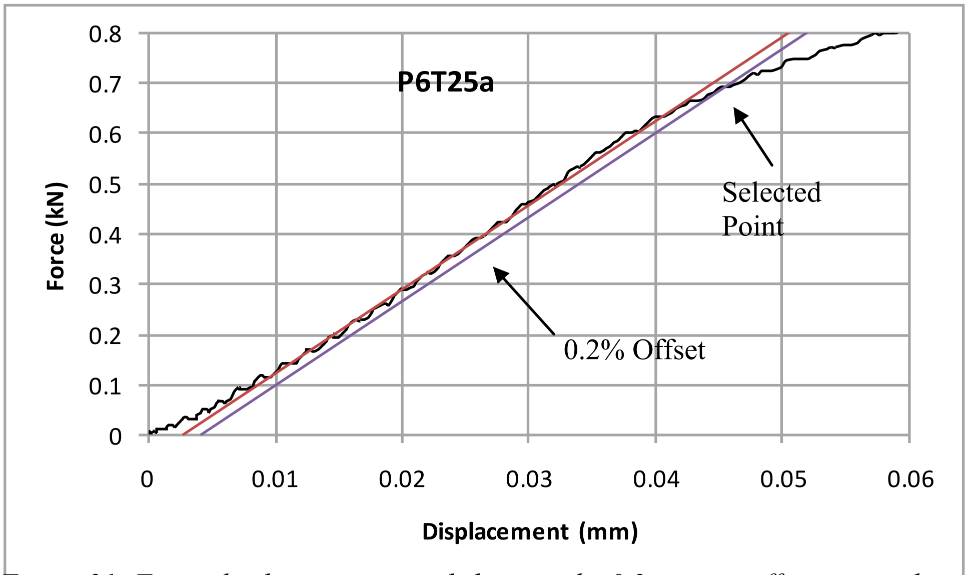

Figure 21: Force-displacement record showing the 0.2 percent offset point selected from the data record for correlation with the material uniaxial yield stress.

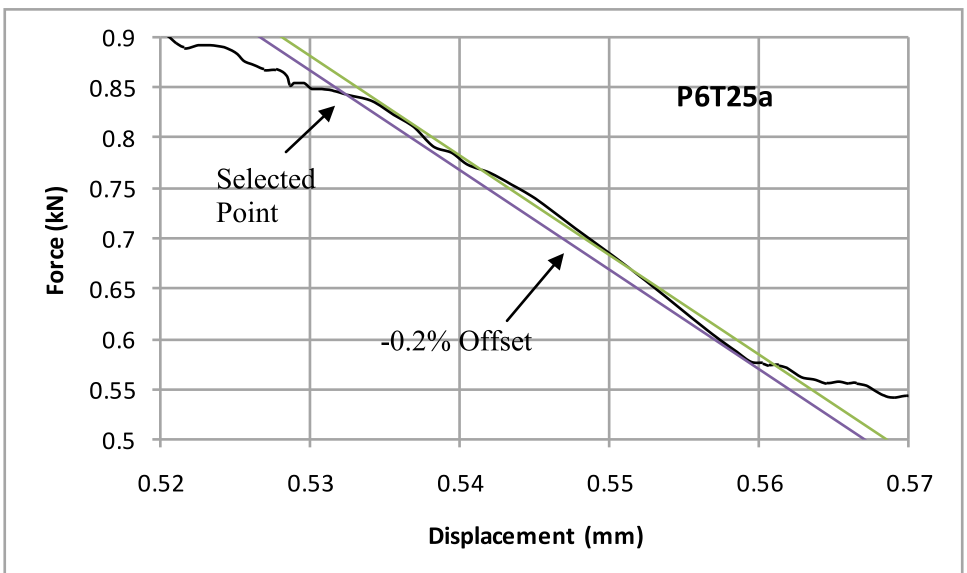

Figure 22: Force-displacement record showing the -0.2 percent offset point selected from the data record for correlation with the material uniaxial failure strain.

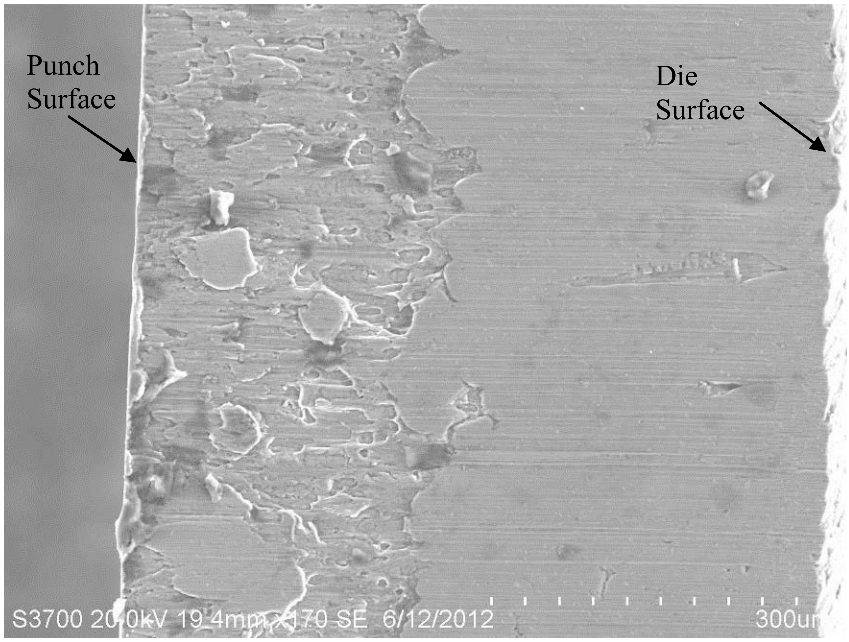

Figure 23: SEM image showing the typical topographical features observed on the edge of the circular slug generated by the shear punch fixture.

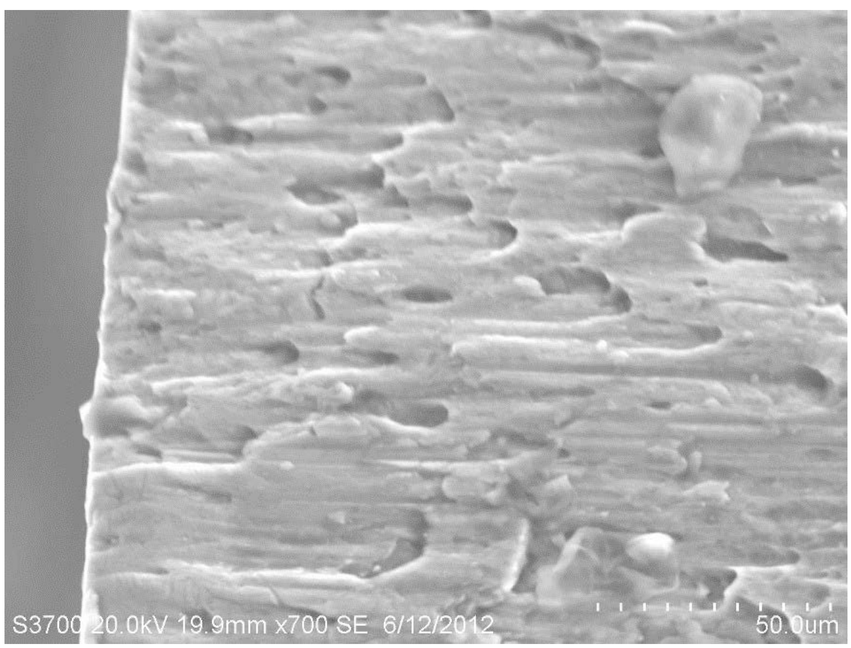

Figure 24: SEM image showing the elongated void formation (Mode II tearing) on the section of the edge adjacent to the top (punch) surface of the slug.

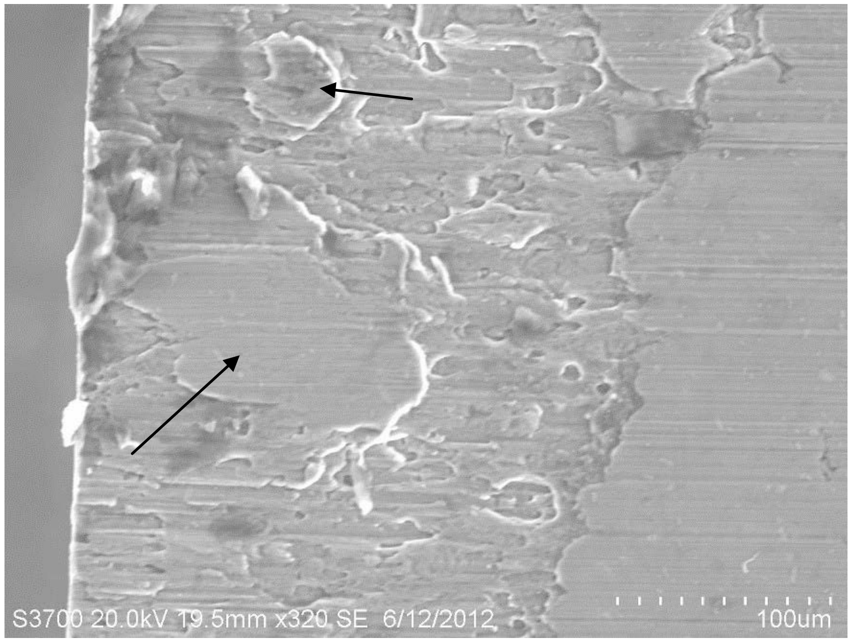

Figure 25: SEM image showing the areas of secondary shear (arrows) contained within the band of material dominated by Mode II tearing.

Figure 26: Micrograph showing the typical metallurgical condition of the aluminum 3003 material utilized for the shear punch tests conducted.

Table 3: Summary of effective stress and strain values calculated from the shear punch tests.

Specimen	6 mm Punch Diameter, 0.70 mm Specimen Thickness		
	0.2% Offset Stress (MPa)	Ultimate Stress (MPa)	-0.2% Offset Strain (%)
P6T25a	52.5	86.3	68.4
P6T25b	58.0	84.2	63.7
P6T25d	40.1	83.3	68.0
Average	50.2	84.6	66.7
Specimen	6 mm Punch Diameter, 0.28 mm Specimen Thickness		
	0.2% Offset Stress (MPa)	Ultimate Stress (MPa)	-0.2% Offset Strain (%)
P6T10a	41.4	92.6	76.2
P6T10b	49.5	90.9	77.2
P6T10c	57.9	90.57	80.27
Average	49.6	91.3	77.9
Specimen	3 mm Punch Diameter, 0.70 mm Specimen Thickness		
	0.2% Offset Stress (MPa)	Ultimate Stress (MPa)	-0.2% Offset Strain (%)
P3T25a	58.9	93.6	59.9
P3T25b	84.5	98.7	56.0
P3T25c	64.1	100.1	60.4
Average	69.1	97.6	58.8
Specimen	3 mm Punch Diameter, 0.28 mm Specimen Thickness		
	0.2% Offset Stress (MPa)	Ultimate Stress (MPa)	-0.2% Offset Strain (%)
P3T10a	68.3	111.4	72.3
P3T10b	102.0	107.7	60.6
P3T10c	105.8	108.5	43.5
Average	92.0	109.2	58.8

4 SUMMARY AND CONCLUSIONS

An experimental shear punch assembly has been designed and fabricated for the evaluation of the mechanical properties of thin metallic materials. While the basic design of the apparatus fabricated is similar to those described in the literature [2], a close-coupled compression force transducer and the direct measurement of specimen displacement response during the test procedure has been incorporated into the design.

The results of validation experiments conducted with the apparatus indicates that with the exception of the 3 mm punch diameter and 0.28 mm specimen thickness combination, in general, for a given punch diameter and specimen thickness combination, the calculated effective yield stress, ultimate stress, and strain are reproducible. A comparison of the results generated by the differing punch diameter and specimen thicknesses combinations indicates a good agreement between the effective stress parameters calculated using the 6 mm punch diameter for the specimen thicknesses tested. Effective stress values from the 3 mm punch diameter tests were elevated as compared with the 6 mm diameter tests and tended to increase with decreasing specimen thickness. The effective strain parameter calculated exhibited reasonable agreement between 3 mm and 6 mm punch diameters for the 0.70 mm and 0.28 mm thick specimen experiments conducted.

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List of symbols/abbreviations/acronyms/initialisms

ASTM	American Society for Testing and Materials
DC	Direct Current
DRDC	Defence Research and Development Canada
FSP	Friction Stir Processing
LVDT	Linear Variable Displacement Transducer
MMC	Metal Matrix Composite
MTS	Materials Test System
SPTF	Shear Punch Test Fixture

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Development and Validation of a Shear Punch Test Fixture

4. AUTHORS (last name, followed by initials – ranks, titles, etc. not to be used)

KarisAllen K.J.

5. DATE OF PUBLICATION (Month and year of publication of document.) August 2013	6a. NO. OF PAGES (Total containing information, including Annexes, Appendices, etc.) 40	6b. NO. OF REFS (Total cited in document.) 6

7. DESCRIPTIVE NOTES (The category of the document, e.g., technical report, technical note or memorandum. If appropriate, enter the type of report, e.g., interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

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10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.) FR-SHEAR120331	10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.) DRDC Atlantic CR 2012-070

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An experimental shear punch assembly has been designed and fabricated for the evaluation of mechanical strength properties of metallic materials. The shear punch tester uses very small, thin specimens to evaluate shear behaviour of materials, the results of which can be correlated to tensile behaviour of the material. The apparatus provides a means of evaluating the mechanical properties of metal matrix composites (MMC) manufactured by friction stir processing (FSP) that are being developed as part of a Technology Investment Fund (TIF) project, as the volume of materials produced are too small for conventional tensile test methods. The shear punch apparatus has a similar basic design to those described in the literature; however a close-coupled compression force transducer and the direct measurement of specimen displacement response during the test procedure have been incorporated. This provides a direct measurement of both force and specimen displacement which improves the accuracy of the measured material response. This report also details the validation of the apparatus using 3xxx series aluminium specimens. The results indicate that for a given punch diameter and specimen thickness combination, the calculated effective yield stress, ultimate stress and strain are generally reproducible.

Un appareil expérimental d’essai de cisaillement et de perforation a été mis au point et fabriqué dans le but d’évaluer les propriétés de matériaux métalliques sur le plan de la résistance mécanique. Celui-ci ne nécessite que de très petits échantillons pour établir le comportement de matériaux soumis à un essai de cisaillement, dont les résultats peuvent être corrélés à la résistance à la traction des matériaux. L’appareil permet d’évaluer les propriétés mécaniques de composites à matrice métallique qui sont fabriqués par friction-malaxage dans le cadre d’un projet du Fonds d’investissement technologique, mais les quantités produites sont très petites pour se prêter à des essais de traction classiques. Sa conception fondamentale est similaire à celle d’autres appareils décrits dans des ouvrages pertinents, mais elle comprend un transducteur de force de compression à couplage direct et implique la mesure directe du mouvement des échantillons pendant les essais. L’appareil permet donc de mesurer directement le mouvement de la force et des échantillons, ce qui procure des mesures plus exactes de la réaction des matériaux éprouvés. Le présent rapport traite en détail de la validation de l’appareil au moyen d’échantillons d’aluminium de la série 3xxx. Les résultats de cette dernière montrent qu’en conjuguant un diamètre de perforation donné à une épaisseur d’échantillon particulière, il est généralement possible de reproduire la limite réelle d’élasticité, la contrainte de rupture et la déformation calculées.

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mechanical testing; shear; punch; material properties; tensile; ductility; strength

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